Agricultural and Forest Meteorology 253–254 (2018) 1–14

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Adaptation strategies to lessen negative impact of climate change on grain maize under hot climatic conditions: A model-based assessment

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ARTICLE INFO

Keywords:
Modelling
Cultivar
Sowing date
Extreme temperature

ABSTRACT

Rise in temperature, particularly in warmer areas, could have a negative effect on maize productivity. However, careful management practices could reduce the effects of high temperatures by altering the sowing dates and type of cultivar. The current study applied APSIM (The Agricultural Production Systems sIMulator) crop model to investigate the interaction of sowing date and cultivar when dealing with climate change and high temperatures at nine locations in Khuzestan province, in southwestern Iran. Daily climatic data for the baseline period of 1980–2010 was obtained from the Meteorological Organization of Iran. Projections of the future climate of Khuzestan was done in Miroc5 (Model for Interdisciplinary Research on Climate) GCM (Global Climate Model) for 2040–2070 under two RCPs (Representative Concentration Pathways) (RCP4.5 and RCP8.5) using the methodology developed by AgMIP (The Agricultural Model Intercomparison and Improvement Project). The high risk window for extreme temperature was calculated as the number of days having a maximum temperature of over 36 °C (Tmax > 36 °C) during pre-flowering and flowering. Results indicated that for mid-future (2050), the average maize grain yield in almost all study areas except Masjed Soleyman decreased in comparison to baseline at −13.7% and −22.8% for RCP4.5 and RCP8.5, respectively mainly because the length of the high-risk window for extreme temperature had expanded from 18.8 to 26.3 days for RCP4.5 and RCP8.5, respectively, compared to baseline. Most farmers have not realized that they are currently sowing maize during a high-risk window for extreme temperatures (Tmax > 36 °C) in some seasons. If farmers do not apply adaptive options for their regions (most promising sowing date × cultivar), the probability of economical grain yield will be less than 50% for an average economical grain yield of 8.9 t ha^{-1}. The current findings support the hypothesis that climate change by the middle of the 21st century will not be beneficial for maize agroecosystems in hot areas like Khuzestan province unless the best sowing date × cultivar is applied for both winter and summer sowing dates.

1. Introduction

Khuzestan province in southwestern Iran (Fig. 1) features a hot climate. With 8.85% of the total area under cultivation in Iran, it is the largest producer of the crops in the country. The province produces 78,318 ha of maize (33.5% of cultivated area) equaling about 29.7% of the maize production in Iran (Anonymous, 2014a), but the average grain yield for a farm (5 t ha^{-1}) does not meet the highest potential yield (Agricultural Jihad Organization of Khuzestan Province, 2016; personal communication).

Over the past three decades, the mean temperature of Khuzestan province has risen about 1.96 °C (Dashtbozorgi et al., 2015). The rise in temperature, particularly in warmer areas, could have a negative effect on maize productivity by decreasing the length of the growing season (Liu et al., 2010; Olesen, 2005; Porter, 2005; Tubiello et al., 2000), pollen viability and seed set (Dupuis and Dumas, 1990; Hatfield and Prueger, 2015; Herrero and Johnson, 1980; Lobell et al., 2015; Singh et al., 2015, 2016).

Careful management practices could reduce the exposure of the flowering stage to high temperatures by altering the sowing dates and type of cultivar. Farmers in Khuzestan province usually sow maize in the winter and summer with flowering stages occurring between 30 April and 23 May and 21 September and 6 October, respectively. Experts around the world have generally reported that early sowing dates for winter cultivation and late sowing for summer cultivation can be considered to avoid heat stress (Liu et al., 2013; Zheng et al., 2012).

The use of a cultivar having a different maturation schedule could also limit the impact of heat stress. The flowering stage of the cultivar depends on the time of leaf appearance, photoperiod sensitivity and other cultivar-specific parameters (Kumudini et al., 2014). To decrease the risk of heat stress under climate change, the effects of the interaction of cultivar, season and sowing date (G × E × M) should be

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https://doi.org/10.1016/j.agrformet.2018.01.032
Received 9 March 2017; Received in revised form 20 November 2017; Accepted 23 January 2018
Available online 02 February 2018
0168-1923/

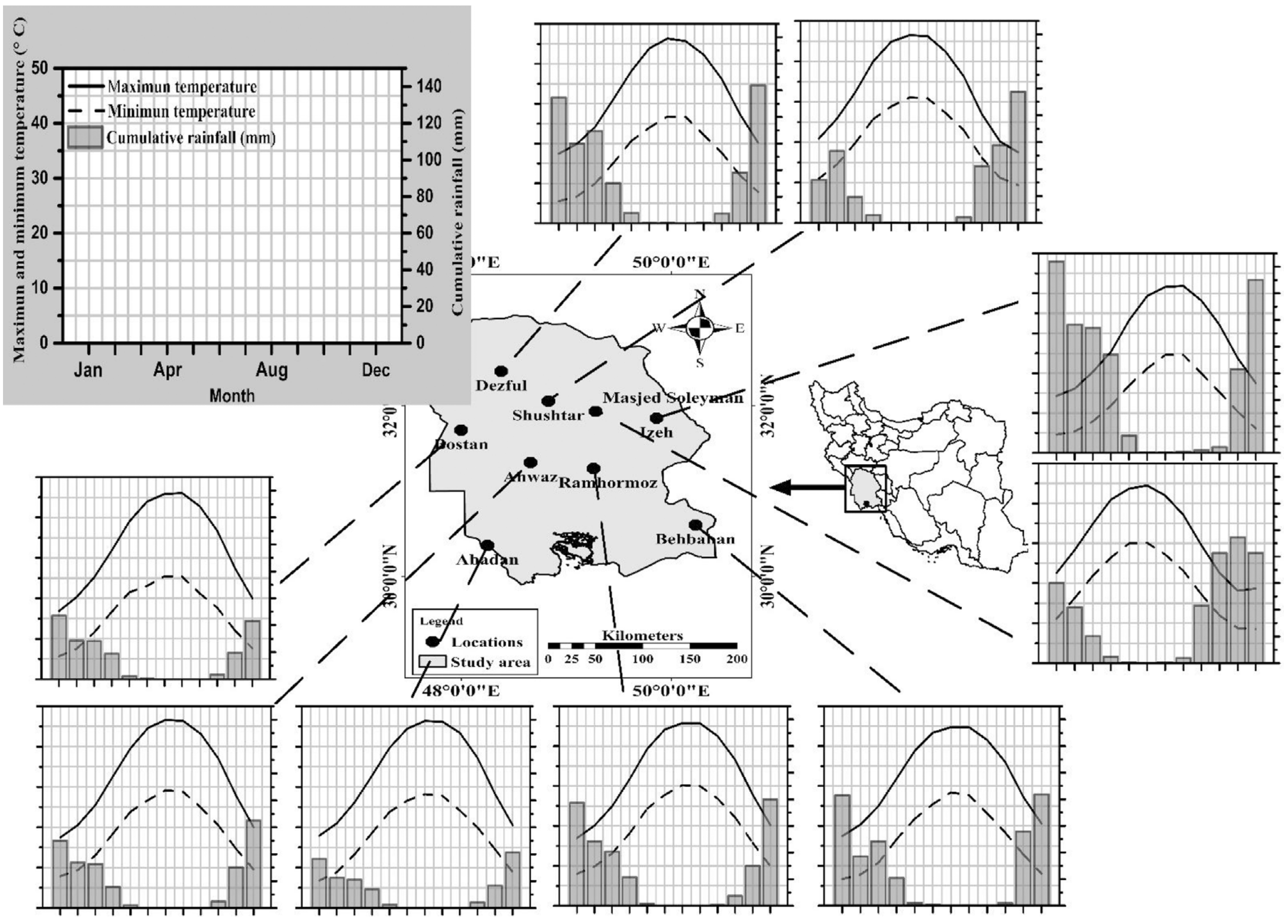

Fig. 1. Geographical details and long-term monthly cumulative rainfall (columns) and maximum (solid line) and minimum (dash line) temperatures of meteorological stations at study locations averaged from 1980 to 2010. Scales are given in this shaded box at the top-left of the figure.

considered.

Liu et al. (2013) reported that early sowing dates combined with cultivars having higher thermal time requirements lessened the negative impact of global warming on maize grain yield in northeastern China. Alexandrov and Hoogenboom (2000) studied the impact of climate variability and changes on crop yield in Bulgaria and found that adaptation strategies such as changes in sowing date and hybrid selection could potentially reduce the impact of climate change on maize production. Moradi et al. (2013) reported the positive effects of early sowing date on maize yield under climate change conditions in northeastern Iran.

Simulation models can be used to evaluate environmental impact of climate change (Chenu, 2015; Chenu et al., 2013; Zheng et al., 2012). Feasible roles of crop simulation models include assessing the effect of agricultural management practices on crop productivity (Amiri et al., 2016; Brisson et al., 2003; Deihimfard et al., 2015; Jones et al., 2003) and of climate change on crop yield (Asseng et al., 2011; Lobell et al., 2015; Zheng et al., 2012). These have been shown to be suitable for assessing the effects of climate change on crop yield (Asseng et al., 2011; Liu et al., 2012; Zheng et al., 2012), the effect of sowing date and cultivar (Liu et al., 2013; Zheng et al., 2012) and of high temperatures (Lobell et al., 2015). APSIM model is one of the crop simulation models that has the ability to accurately simulate the management effects on crops (e.g. Deihimfard et al., 2015) and the effects of extreme temperatures on maize growth, pollen viability and seed set (e.g. Lobell et al., 2015, 2013). In addition, this model has been evaluated for many crops (such as wheat and maize) and cultivars under Iranian climatic and management conditions with high accuracy (e.g. Deihimfard et al., 2015; Soltani and Sinclair, 2015; Abbaspour et al., 2014).

The current study applied Agricultural Production Systems sIMulator (APSIM crop model) to investigate the interaction of sowing date and cultivar when dealing with climate change and high temperatures. The objectives of the current study were (i) to assess the effects of climate change and high temperatures on the maize yield in Khuzestan province, (ii) to determine the high-risk windows for heat stress during the flowering stage in each region of Khuzestan province and (iii) to evaluate the role of adaptation strategies (sowing date and cultivar) to lessen the negative impact of climate change on maize productivity under the hot climatic conditions of Khuzestan province.

2. Materials and methods

2.1. Study locations

The current study was conducted in Khuzestan province, located in the sub-humid agro-climatic zone of southwestern Iran (Fig. 1). The study focused on nine locations in Khuzestan province: Abadan, Ahwaz, Behbahan, Bostan, Dezful, Izeh, Masjed Soleyman, Ramhormoz and Shushtar (Fig. 1). The criteria for selection these locations were the size of the area under maize cultivation, climatic diversity and province-wide distribution.

2.2. Weather data and climate scenarios

Daily climatic data for the baseline period of 1980–2010 was obtained from the Meteorological Organization of Iran. The climatic data contained the duration of sunlight (h), maximum and minimum air temperature (°C) and precipitation (mm). As the daily solar radiation

($MJ\,m^{-2}\,d^{-1}$) is required for running crop simulation models and normally not measured in many weather stations, it was estimated using Angstrom equation as follows (Prescott, 1940):

$$R_s = \left(a + b\frac{n}{N}\right)R_a \tag{1}$$

where R_s is the global solar radiation at the ground surface ($MJ\,m^{-2}\,d^{-1}$), n is the actual duration of sunlight (h), N is day length (h), R_a is extraterrestrial radiation ($MJ\,m^{-2}\,d^{-1}$) and a and b are Angstrom coefficients. Parameters a and b for the different study locations were 0.317 and 0.386, respectively (Moini et al., 2011).

Climatic data at baseline was used as the basis of future climate scenario analysis. Future climatic scenarios were produced using the delta scenario of the CMIP5 General Circulation Model (GCM) and the climate scenario generation tools in R as introduced in the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Araya et al., 2015; Hudson and Ruane, 2013; R Core Team, 2013; Ruane et al., 2013a,b; AgMIP, 2013; Wilby et al., 2004). For a given location, this approach generates climate scenarios by adjusting historically-observed climate data using the predicted absolute change in minimum and maximum air temperature and relative change in rainfall in the climate model (Ruane et al., 2013b; Wilby et al., 2004). Projections of the future climate of Khuzestan was done in Miroc5 (Model for Interdisciplinary Research on Climate) GCM (Watanabe et al., 2010) for 2040–2070 under RCP4.5 and RCP8.5 using the methodology developed by AgMIP (Hudson and Ruane, 2013; Ruane et al., 2013a). The MIROC5 GCM was applied because it showed the highest accuracy for projection of the climate data of the study area compared with the other GCMs (Dashtbozorgi et al., 2015; Dashtbozorgi, 2015). According to the previous study, Dashtbozorgi et al. (2015) analyzed the future climate conditions of Khuzestan province till 2050s based upon four RCP scenarios (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) and used MarkSim program as the downscaled model. To assess the accuracy of the simulation model for regional temperature changes, they evaluated three high-resolution GCMs included HadGEM2-ES (1.2414×1.875)[1], MIROC5 (1.4063×1.4063) and MRI-CGCM3 (1.125×1.125) amongst all GCMs of MarkSim model. Regarding the variance analysis, the MIROC5 model was considered as an appropriate model for projecting of the climate data in Khuzestan province ($p = .05$). The future projected changes in daily maximum and minimum temperatures and cumulative seasonal rainfall for the maize growing seasons are displayed in Table 1 for the all study locations.

2.3. Crop model evaluation

APSIM was designed by Australian researchers and has a good ability to simulate the growth and yield of various crops (Keating et al., 2003). The maize module (APSIM-maize) simulates the growth and development of maize on a daily basis and responds to the factors of climate (temperature, precipitation and radiation), soil (water and nitrogen), crop characteristics (i.e. genetic coefficients or cultivar specific parameters) and management practices (e.g. sowing date and irrigation). More details regarding the maize module can be found in Holzworth et al. (2014).

APSIM-maize version 7.7 was applied in this study. The evaluation model consisted of model calibration and validation. For APSIM-maize calibration, different datasets were applied for two major maize cultivars (Table 2). Field experiments were conducted in 2007, 2008, 2011 and 2012 to calibrate the early-maturing cultivar (SC260). Two independent field experiments were applied to calibrate the late-maturing cultivar (SC704) (Table 2). In these experiments, aboveground biomass, number of days from emergence to flowering, number of days from flowering to physiological maturity, leaf area index (LAI) and grain yield were measured. Calibration was done using a trial-and-error protocol to minimize the difference between observed and simulated values. Calibration adjusted the cultivar-specific parameters that highly influenced the relevant trait (i.e. dry matter and LAI) by iterating the model to find the closest match between observed and simulated values in all treatments. Table 3 shows the values of the cultivar-specific parameters obtained through the model calibration.

Independent data from other field experiments were used for model validation. These independent datasets included published articles and final reports of research projects (Table 4). The experiments were conducted for a range of years and locations in Iran under the treatments of sowing date, cultivar, row spacing and plant density. The validation was performed under potential situations (without water and nitrogen limitations).

To measure the difference between observed and simulated variables, the coefficient of determination (R^2), root mean squared error (RMSE) (Wallach and Goffinet, 1987) and index of agreement (d value) (Willmott, 1982) were calculated as:

$$RMSE\,(\%) = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \times \frac{100}{\overline{O}} \tag{2}$$

$$d = 1.0 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i - \overline{O}| + |O_i - \overline{O}|)^2}\right] \tag{3}$$

where S is the simulated data, O is the observed data, $\overline{O}$ is the mean of the observed data and n is the number of observations. An RMSE approaching zero signifies the high accuracy of the model simulation. The d value ranges from 0 to 1 with 1 denoting a perfect match between the observed and simulated data. In addition to RMSE and d, the 1:1 line and linear regression were also applied to identify any relationship between observed and simulated data.

2.4. Simulation of extreme temperature events during flowering stage

In maize, the seed set is a phonological stage that is very sensitive to extreme temperature (Dupuis and Dumas, 1990; Hatfield and Prueger, 2015; Herrero and Johnson, 1980). Studies have shown that a decrease in seed set occurring at extreme temperatures above 38 °C are primarily the result of a decrease in pollen germination ability and pollen tube elongation (Carberry et al., 1989; Dupuis and Dumas, 1990; Stone, 2000). These decreases occur during a 10-day period that includes preflowering and flowering (G.L. Hammer, pers. comm.).

The high risk window for extreme temperature was calculated as the number of days having a maximum temperature of over 36 °C (Tmax > 36 °C) during pre-flowering and flowering (Lobell et al., 2015; Singh et al., 2015, 2016; Hammer, pers. comm.). To better consider the risk of extreme temperatures on grain yield, the simulated grain yields were divided into economical, uneconomical and null grain yield categories. The Agricultural Jihad Organization of Khuzestan province in Iran defined the economical grain yield of Khuzestan as being $\geq 4.5\,t\,ha^{-1}$ and uneconomical grain yield as being $< 4.5\,t\,ha^{-1}$. Null grain yield is defined when there is no grain set despite a large amount of biomass is produced.

Long-term simulation experiments consisted of a factorial of three cultivars, six sowing dates, nine locations and two future scenarios (RCP4.5 and RCP8.5) over a span of 30 years (a total of 14,580 simulation experiments). The baseline and future periods were 1980–2010 and 2040–2070, respectively. The cultivars were SC704 (a late-maturity cultivar) and SC260 (an early-maturity cultivar). SC704 is the predominant cultivar in Khuzestan province; more than 90% of the maize cultivated is of this cultivar. To allow investigation of all rates of maturity of cultivars (early-, mid- and late-maturity), a hypothetical cultivar (HC) was defined in the APSIM model as a mid-maturity cultivar. HC features characteristics between those of SC704 and SC260 and was obtained by modifying the cultivar-specific parameters in APSIM.

[1] Model (Longitude ° × Latitude °).

Table 1
The future projected changes in daily maximum (MaxT) and minimum (MinT) temperatures and cumulative seasonal precipitation (Precip) for the maize winter and summer growing seasons in all study locations. The average of baseline values from 1980 to 2010 are given in Fig. 1.

Location	RCP4.5						RCP8.5					
	Change in winter season			Change in summer season			Change in winter season			Change in summer season		
	MaxT (°C)	MinT (°C)	Rainfall (%)	MaxT (°C)	MinT (°C)	Rainfall (%)	MaxT (°C)	MinT (°C)	Rainfall (%)	MaxT (°C)	MinT (°C)	Rainfall (%)
Abadan	2.1	1.9	1.1	2.2	2.1	−2.7	2.7	2.6	−6.4	3.2	3.2	12.8
Ahwaz	2.5	2.0	0.9	2.5	2.5	3.8	3.1	2.9	−6.5	3.7	3.8	3.7
Behbahan	2.3	2.0	5.4	2.3	2.4	−4.3	2.9	2.8	−8.5	3.4	3.5	6.1
Bostan	2.5	2.0	1.3	2.5	2.5	3.3	3.1	2.9	−8.3	3.7	3.8	4.5
Dezful	2.5	2.0	−2.1	2.5	2.5	12.2	3.2	2.8	−5.1	3.7	3.7	10.7
Izeh	2.7	1.9	2.3	2.6	2.5	−10.6	3.3	2.8	−10.2	3.7	3.7	−5.3
Masjed Soleyman	2.5	2.0	12.8	2.5	2.5	12.9	3.2	2.8	3.6	3.7	3.7	−0.9
Ramhormoz	2.5	2.0	2.2	2.5	2.5	3.8	3.1	2.9	−5.7	3.7	3.8	4.4
Shoshtar	2.5	2.0	16.8	2.5	2.5	15.3	3.2	2.8	5.8	3.7	3.7	7.0

Table 2
Experiments used for APSIM-Maize model calibration.

Cultivar	Location	Year	Treatment	Sowing date	Soil texture	Climate type	Latitude and Longitude	Reference
SC704	Kerman	2014	Cultivar × nitrogen	3th May	Clay loam	Warm and dry	30.25 48.28	Madadizadeh (2017)
SC704	Khormabad	2012	Cultivar	21th May	Clay loam	Moderate and semi-humid	33.43 56.96	Rahimi Moghaddam (2013)
SC260	Shiraz	2007	Cultivar × sowing date	5th June and 15th June	Silty clay loam	Semi- arid	29.53 52.6	Anonymous (2016)
SC260	Shiraz	2008	Cultivar × sowing date	5th June and 15th June	Silty clay loam	Semi-arid	29.53 52.6	
SC260	Shiraz	2011	Cultivar	9th July	Silty clay loam	Semi- arid	29.53 52.6	
SC260	Shiraz	2012	Cultivar	5th July	Silty clay loam	Semi- arid	29.53 52.6	

Table 3
Cultivar-specific parameters of the cultivars obtained from APSIM-Maize model calibration.

Parameter	Abbreviation	Cultivar			Unit
		SC704	HC[a]	SC260	
Thermal time accumulation from flowering to maturity	tt_flower_to_maturity	1000	940	780	°C d
Maximum number of grains per head	head_grain_no_max	650	580	545	–
Thermal time accumulation from seedling emergence to end of juvenile phase	tt_emerg_to_endjuv	270	250	225	°C d
Thermal time accumulation from end of juvenile to floral initiation	tt_ endjuv_to_init	30	0	0	°C d
Grain growth rate	grain_gth_rate	8.5	9.3	9.6	mg kernel^{-1} d^{-1}
Thermal time accumulate on from flag leaf appearance to flowering	tt_flag_to_flowering	50	50	10	°C d
Thermal time accumulation from flowering to start of grain filling	tt_flower_to_start_grain	120	120	120	°C d

[a] To allow investigation of all rates of maturity of cultivars (early-, mid- and late-maturity), a hypothetical cultivar (HC) was defined in the APSIM model as a mid-maturity cultivar. HC features characteristics between those of SC704 and SC260 and was obtained by modifying the cultivar-specific parameters in APSIM.

Maize crops in most of the study area are typically sown in both winter (usually on 19 February) and summer (usually on 15 July). Accordingly, three winter sowing dates (1 February, 19 February and 5 March) and three summer sowing dates (15 July, 31 July and 15 August) were chosen as simulation treatments. These sowing windows were identical for all locations and years. All simulations were conducted under optimum conditions without nitrogen and water limitations. Accordingly, automatic irrigation switched on in the irrigation module of APSIM-Maize model and “fraction of ASW below which irrigation is applied” criteria was also set as 0.9. Also, at each phenological stage of maize, enough nitrogen was applied to prevent any stress on maize. Row spacing (750 mm), sowing depth (50 mm), tillage (conventional) and other management practices were kept constant as optimal throughout all simulations. Densities were considered 7, 7.5 and 8 plants m^{-2} for late-maturity (SC704), mid-maturity (HC) and early-maturity (SC260) cultivars. All the outputs obtained from the model were subject to analysis, graphing and mapping using the R software package (R Core Team, 2013), OriginPro 9.1 (Seifert, 2014) and ArcGIS 10.1 (ESRI, 2012).

3. Results

3.1. Model evaluation

The results of model calibration using the data collected from different locations and seasons (Table 2) showed that the simulated days to flowering and maturity and aboveground biomass were modeled reasonably well for the two cultivars (Table 5 and Fig. 2). The difference between the observed and simulated values for SC704 were 1 day, 2.5 day and 0.7 t ha^{-1} for days to flowering, days to maturity and aboveground biomass, respectively. These values for SC260 were equal to 1.5 day, 3.3 day and 0.3 t ha^{-1}, respectively. Across two cultivars (SC704 and SC260), RMSE and *d* for days to flowering were 1% and 0.99, respectively, and for days to maturity were 1.5% and 0.98,

Table 4
Experimental data used for model validation for SC704 and SC260 cultivars.

Cultivar	Location	Latitude and Longitude	Year	Treatments	Soil texture	Climate type	Reference
SC704	Zarghan	29.78 52.71	2007	Sowing date	Silty clay loam	Semi- arid	Estakhr and Choukan (2011)
SC704	Zarghan	29.78 52.71	2005, 2006	Cultivar × sowing date	Silty clay loam	Semi- arid	Dehghanpour and Estakhr (2010)
SC704	Shiraz	29.53 52.6	2007	Sink-Source Restriction	Silty clay loam	Semi- arid	Emam et al. (2013)
SC704	Gorgan	36.9 54.4	2004	Plant density	Clay loam	Moderate and humid	Saberi et al. (2008)
SC704	Gorgan	36.9 54.4	2008	Plant density × sowing date	Clay loam	Moderate and humid	Moeinirad et al. (2013)
SC704	Mianeh	37.45 47.7	1999	Row spacing × plant density	Clay loam	Moderate and semi-humid	Salehi (2005)
SC704	Karaj	35.91 50.98	2012	Cultivar	Clay	Semi- arid	Choukan (2013)
SC704	Moghan	39.65 47.91	2012	Cultivar	Clay loam	Warm and humid	Choukan (2013)
SC704	Gharakhil	36.45 52.76	2012	Cultivar	Clay loam	Moderate and humid	Choukan (2013)
SC704	Esfahan	32.61 51.66	2012	Cultivar	Clay loam	Semi- arid	Choukan (2013)
SC704	Shiraz	29.53 52.6	2012	Cultivar	Silty clay loam	Semi- arid	Choukan (2013)
SC704	Gorgan	36.9 54.4	2012	Cultivar	Clay loam	Moderate and humid	Choukan (2013)
SC704	Kermanshah	34.35 47.15	2012	Cultivar	Silty loam	Moderate and semi-humid	Choukan (2013)
SC704	Jiroft	28.58 57.8	2012	Cultivar	Loam	Warm and dry	Choukan (2013)
SC704	Ilam	33.63 46.43	2012	Cultivar	Silty clay loam	Moderate and semi-humid	Choukan (2013)
SC260	Zarghan	29.78 52.71	2005, 2006	Cultivar × sowing date	Silty clay loam	Semi- arid	Dehghanpour and Estakhr (2010)
SC260	Mashhad	36.26 59.63	2008	Cultivar	Loam	Semi- arid	Hasanzadeh and Dehghanpour (2010)
SC260	Mashhad	36.26 59.63	2006	Cultivar × plant density	Loam	Semi- arid	Goldani et al. (2011)
SC260	Khormabad	33.43 56.96	2005	Plant density × sowing date	Clay loam	Moderate and semi-humid	Naderi et al. (2010)

respectively. Model accuracy for prediction of LAI was not as good as for the above-mentioned variables, with RMSE and *d* values of 9.48% and 0.99, and 16.7% and 0.98, respectively, for two experiments (Fig. 2). The results of model evaluation for grain yield using data obtained from 19 experiments across different locations, years and cultivars (Table 4) indicated that the model accurately simulated maize grain yield with RMSE, *d* value and R^2 of 8.94%, 0.93 and 0.82 for SC704, and 9.26%, 0.96 and 0.87 for SC260, respectively (Fig. 3).

3.2. Grain yield at baseline: cultivar × sowing date

There was large variability in grain yield at baseline depending upon sowing date and cultivar for all study locations except Izeh. The average grain yield of the entire province was 6.4 t ha^{-1} (Fig. 4). At a given location, the response of grain yield to sowing date and cultivar was significant; yield ranged from 1.8 to 11 t ha^{-1} depending on the cultivar and sowing date. The highest and lowest average grain yield simulated for Izeh and Masjed Soleyman was 10.1 and 4.4 t ha^{-1}, respectively (Fig. 4). Some null grain yields (0 t ha^{-1}) were predicted for some locations and seasons. For instance, despite the production of an average aboveground biomass of 19.8 t ha^{-1} in Shushtar (data not shown), a null grain yield was predicted for about 33% of seasons (Fig. 5). In Masjid Soleyman an average aboveground biomass of 19.7 t ha^{-1} was simulated with a null grain yield in about 42.8% of seasons (Fig. 5).

For winter sowing dates, averaged across locations and cultivars, the number of seasons with economical, uneconomical and null grain yields were 61%, 11.1% and 27.4%, respectively. On average, early sowing dates exhibited the highest number of seasons with economical grain yield (75.1%) and the late sowing dates exhibited the lowest (45.2%). For example, the highest probability of economical grain yield (100%) was recorded for SC260 on 1 February in Behbahan and Ramhormoz and for HC and SC260 on 19 February in Izeh (Fig. 5). Under the worst conditions, 100% of years with late winter sowing dates produced null grain yields in Shushtar for HC and SC704 (Figs. 4 and 5). Averaged across locations and winter sowing dates, the highest economical grain yield was simulated for HC (9.6 t ha^{-1}) followed by SC704 (9.4 t ha^{-1}) and SC260 (8.1 t ha^{-1}) (Fig. 4).

For summer sowing dates at baseline, the highest economical grain yield was for SC704 on 15 July in Izeh (11.1 t ha^{-1}) while the lowest economical grain yield was obtained for SC260 on 15 July in Behbahan (5.7 t ha^{-1}) (Fig. 4). Averaged across locations and summer sowing

Table 5
Results of APSIM model calibration for the SC704 and SC260 cultivars in different Locations and years.

Cultivar	Location	Sowing date	Days to flowering (DOY[a])		Days to maturity (DOY)		Aboveground biomass (t ha^{-1})	
			Observed	Simulated	Observed	Simulated	Observed	Simulated
SC704	Kerman	3th May	192	192	253	255	26.95	27.69
SC704	Khoramabad	21th May	207	209	267	260	24.46	25.12
SC260	Shiraz	5th June	212	211	255	258	19.37	19.08
SC260	Shiraz	15th June	221	223	265	267	18.73	19.44
SC260	Shiraz	5th June	213	212	256	259	19	18.86
SC260	Shiraz	15th June	222	225	266	270	18.33	18.69
SC260	Shiraz	9th July	243	245	293	299	18.54	19.23
SC260	Shiraz	5th July	244	248	293	295	19.17	19.67
Mean			219.3	220.6	270.4	268.5	20.97	20.56
RMSE				1%		1.50%		2.63%
d value				0.99		0.98		0.99
n				8		8		8

[a] Day of year.

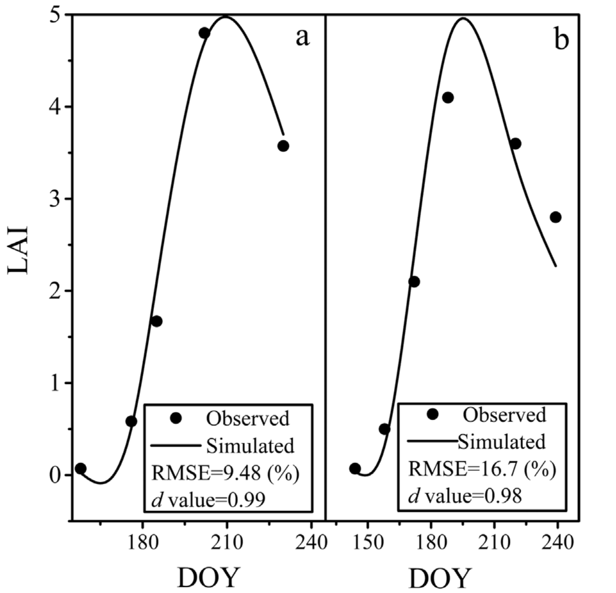

Fig. 2. Calibration of SC704 cultivar for LAI using results of field experiments by: (a) Rahimi Moghaddam (2013), and; (b) Madadizadeh (2017). LAI was not calibrated for SC260 because of lack of data.

dates, however, SC704 and HC with 8.9 t ha^{-1} showed the highest economical grain yields compared with SC260 (5.6 t ha^{-1}) (Fig. 4). Fig. 4 shows that SC260 did not perform well for grain yield in either early or late summer sowing dates at all locations with the exception of Izeh.

As for winter sowing dates, there were some uneconomical and null grain yields for summer sowing dates. SC704 was superior in terms of economical grain yield compared to the other cultivars. When averaged across locations and summer sowing dates, the number of seasons with economical, uneconomical and null grain yields were 79.1%, 9.7% and 11.2%, for SC704, 68.3%, 15.5% and 16.1%, for SC260 and 70.3%, 11.2% and 18.8%, for HC, respectively. Late sowing (31 July) resulted in increased uneconomical and null grain yields particularly for SC704 (Fig. 5). The average winter sowing dates across locations and cultivars was 9 t ha^{-1}, which is better than for the summer sowing dates (8.5 t ha^{-1}) in terms of economical grain yield.

3.3. Effect of climate change on maize yield

For mid-future (2050), the average maize grain yield in almost all study areas except Masjed Soleyman decreased in comparison to baseline at −13.7% and −22.8% for RCP4.5 and RCP8.5, respectively (Fig. 4). The decrease differed by location; the greatest decline was recorded for Behbahan at −21.1% and −33.9% for RCP4.5 and RCP8.5, respectively. The simulated grain yield increased in Masjed Soleyman alone at +12.8 and +13.1% for RCP4.5 and RCP8.5, respectively (Fig. 4). When averaged across locations, seasons and sowing dates, the number of seasons with null grain yields increased 28.2% and 51.5% for RCP4.5 and RCP8.5, respectively, compared to baseline (Fig. 6). In addition, the number of seasons with uneconomical grain yields increased 19.9% and 24.9% for RCP4.5 and RCP8.5, respectively compared to baseline.

For winter sowing dates in the future, the best sowing date and cultivar were identical to baseline; the highest economical grain yield was simulated for SC704 on 1 February in Masjed Soleyman (14.2 and 13.4 t ha^{-1} in RCP4.5 and RCP8.5, respectively). When averaged across locations, seasons, and cultivars, early winter sowing dates recorded higher economical grain yields than for the late sowing dates (9.3 t ha^{-1} vs. 7.1 t ha^{-1} for RCP 4.5 and 9.3 t ha^{-1} vs. 7.4 t ha^{-1} for RCP 8.5) (Fig. 4). When averaged across RCPs, locations and cultivars, the number of seasons with economical, uneconomical and null grain yields were 69%, 15.8% and 14.5% for 1 February, followed by 50.2%, 25.8% and 24%, for 19 February and 28.9%, 36.5% and 34.6% for 5 March (Fig. 6). The probability of producing an economical yield was greater for SC260 (61.8%) followed by HC (47.7%) and SC704 (39.5%) (Fig. 6). Under the worst conditions, the number of seasons with null grain yields was nearly 100% for 5 March in Shushtar for both SC704 and HC under both RCPs (Fig. 6). The number of seasons with null and uneconomical grain yields was also high in Masjed Soleyman at 86% and 86.4% for RCP4.5 and RCP8.5, respectively.

For summer sowing dates in the future, the highest economical grain yield was achieved for SC704 on 31 July in Izeh at 10.3 and 9.9 t ha^{-1} for RCP4.5 and RCP8.5, respectively. The early-maturity cultivar (SC260) did not perform well for all summer sowing dates, locations and RCPs. For example, under extreme conditions in Behbahan on 15 July for RCP8.5, null grain yields were obtained in 100% of seasons (Figs. 4 and 6). For summer sowing dates, the number of seasons with null and uneconomical grain yields increased by 69.9% and 30.6% for RCP8.5 and by 26.1% and 19.8% for RCP4.5, respectively compared to baseline (Figs. 5 and 6). Averaged across locations and summer sowing dates, the number of seasons with economical, uneconomical and null grain yields for RCP4.5 was 76%, 11% and 13% for SC704, 63.5%, 12.5% and 34.6% for HC and 59.1%, 20.1% and 20.8% for SC260. For RCP4.5, the number of seasons with economical, uneconomical and null grain yields was 88.8%, 7.3% and 3.9% for the late sowing date (15 August) and 73.8%, 15.8% and 10.4% for 31 July

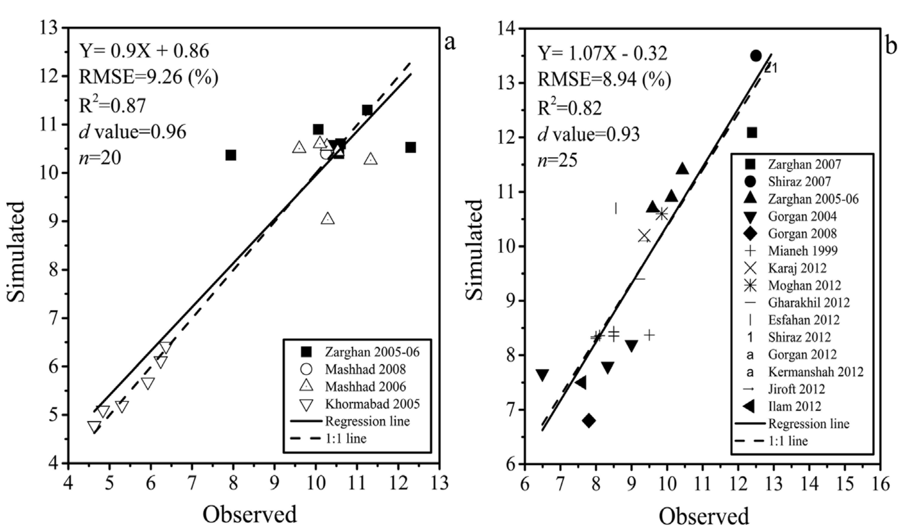

Fig. 3. Results of model validation for grain yield (t ha^{-1}): (a) SC260 and; (b) SC704 cultivar. Symbols are data points for different experiments (Table 3).

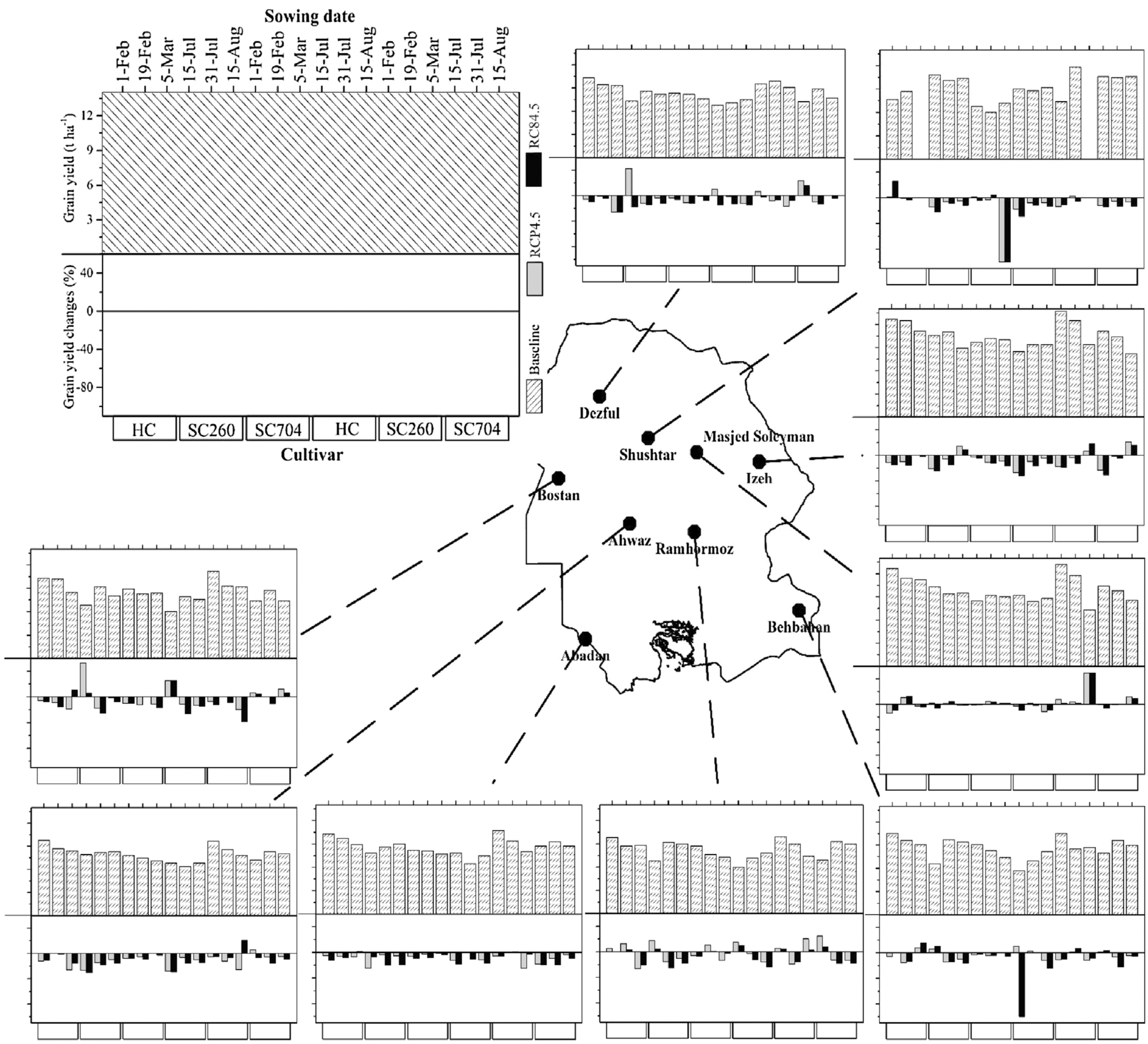

Fig. 4. Simulated economical grain yield by location, sowing date (winter and summer) and cultivar at baseline for 1980–2010 (shaded columns) and its change in the future of 2010–2070 for RCP4.5 (gray columns) and RCP8.5 (black columns) in all study locations. Each point is the mean of 30-year simulations. Economical grain yield was ≥4.5 t ha^{-1} (Agricultural Jihad Organization of Khuzestan province). HC was defined as the mid-maturity cultivar with characteristics between SC704 (late–maturity) and SC260 (early-maturity) and was obtained by modifying the genetic coefficients in APSIM. Scales are given in this shaded box at the top-left of the figure.

and 36%, 20.5% and 43.5% for the early sowing date (15 July) (Fig. 6). Similar results were obtained for the RCP8.5 simulation.

3.4. Effect of risk windows for extreme temperature at flowering stage on maize yield at baseline and in future

Fig. 7 shows the high risk window at Tmax > 36 °C for pre-flowering and flowering for all locations, sowing dates and cultivars at baseline and in future scenarios. At baseline, the longest high-risk window was simulated for Ramhormoz (1 May–19 October; 171 days) and the shortest was for Izeh (28 May–28 September; 123 days) (Fig. 7). The window opened in May in the most locations; however, in the warmer areas of Masjed Soleyman and Shushtar, it began earlier with a high-risk window from 18 March to 21 August and 1 April to 12 September, respectively. At these locations, the high-risk window also closed earlier in September, so the flowering windows for all summer sowing dates and cultivars did not coincide with the extreme temperature risk window. On the contrary, the high-risk window occurred for all winter sowing dates and cultivars in these locations. For instance, for the 1 February sowing date at Masjed Soleyman, the flowering stage for SC260 was 21 March–4 April, which was concurrent with the high-risk window (from 18 March to 21 August) (Fig. 7). Similarly, for summer sowing dates, the flowering stage of SC260 was from 10 September to 16 September in Masjed Soleyman for 15 July, which did not coincide with the high-risk window (18 March–21 August) (Fig. 7).

In the cooler locations like Izeh, the high risk window and flowering stage differed from those in warmer locations. The window began later on 28 May and ended on 28 September at baseline. In all other areas except the warmer ones, of the summer sowing dates, only 15 July fell inside the high-risk window for all cultivars. The 15 August date was 50% outside the risk window, particularly for the late-maturity cultivar (SC704). This depended strongly on the type of cultivar for winter sowing dates. HC and SC260 performed better at early dates (1 February and 5 March), which were outside the high-risk window. In contrast, the flowering of SC704 fell inside the high-risk window for the majority of winter sowing dates (Fig. 7).

By 2050, on average, the length of the high-risk window had expanded from 18.8 to 26.3 days for RCP4.5 and RCP8.5, respectively,

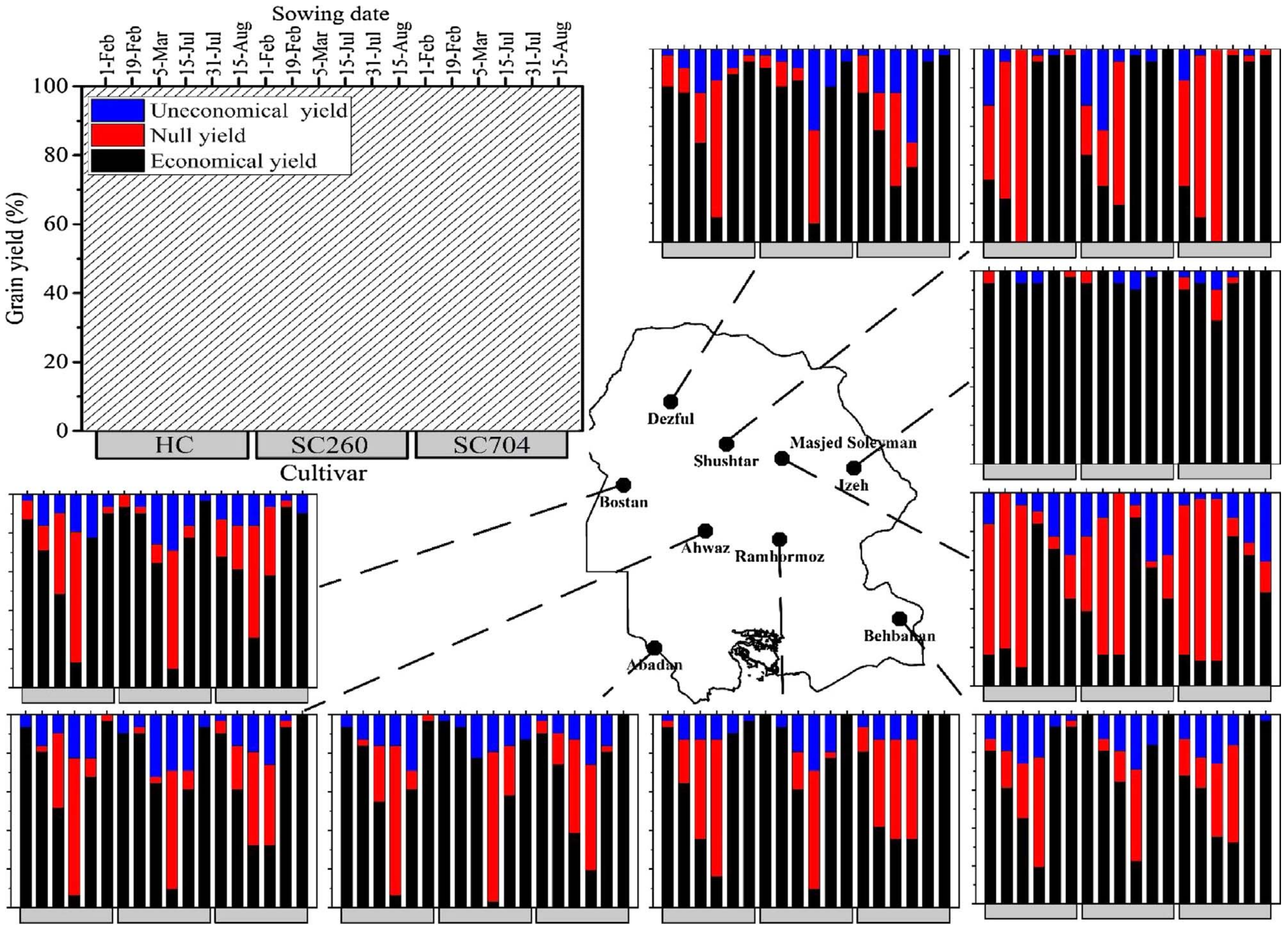

Fig. 5. Percentage of seasons with economical, uneconomical and null grain yields for sowing date × cultivar at baseline. Economical grain yield was ≥ 4.5 t ha^{-1} and uneconomical grain yield was < 4.5 t ha^{-1} (Agricultural Jihad Organization of Khuzestan province). Scales are given in this shaded box at the top-left of the figure.

compared to baseline (Fig. 7). The longest and shortest windows were in Ahwaz for RCP8.5 (15 April–30 October; 199 days) and in Izeh for RCP4.5 (15 May–1 October; 139 days). For all summer sowing dates in the future, the late-maturity cultivar (SC704) at the late sowing date (15 August) experienced less time in the high risk window during the flowering stage for all locations and RCPs. For instance, for the early sowing date in Behbahan (15 July), the flowering period of SC260 (29 September–4 October; 6 days) was entirely within the high-risk window for RCP8.5 (22 April–32 October; 192 days) while for the late sowing date (15 August) at this location (28 October–1 November; 5 days), the flowering date for SC704 did not fall within the high-risk window for RCP8.5 (Fig. 7). Masjed Soleyman and Shushtar were exceptions; the flowering stages for almost all summer sowing dates, cultivars and RCPs occurred outside the high-risk window. By contrast, all the winter sowing dates and cultivars fell within the high-risk window in all seasons at these locations (Fig. 7).

4. Discussion

4.1. Model evaluation

The result of model evaluation revealed that APSIM could simulate growth and development of different maize cultivars with high accuracy in different years, sowing dates and locations. This can be attributed to the excellent simulation of maize phenology. In APSIM model, the accurate prediction of phenology provides a good prediction of the LAI (Holzworth et al., 2014; G.L. Hammer, pers. comm). Among all the key processes and parameters involved in biomass production, LAI is the most important factor to achieve good estimates of biomass production (Archontoulis et al., 2014). Therefore, accurate prediction of the phenology provides a precise prediction of the LAI and, ultimately biomass production. For example, in SC704, the excellent prediction of flowering time resulted in an acceptable estimation of LAI which made accurate simulation of biomass with low difference between observed and simulated values (26.4 and 25.7 t ha^{-1}, respectively). On the other hand, accurate simulation of the phenology also provides a good prediction of the biomass partitioning between different parts of maize at different phenological stages (Holzworth et al., 2014; Keating et al., 2003). Overall, the above items represent the proper structure of APSIM model in simulating the growth and yield of maize crop.

4.2. Choice of sowing date vs. cultivar under current conditions at baseline

The current common sowing date for winter and summer seasons in Khuzestan province are 19 February and 15 July, respectively. The late-maturity cultivar (SC704) recorded the highest percentage of area under cultivation in the study region (Anonymous, 2014b). The results of the study reveal that these sowing dates and cultivar are not optimal for most study locations at baseline; the average number of seasons for uneconomical and null grain yields for SC704 was 47% and 46.2%, respectively, for the common winter and summer sowing dates for the whole province. In other words, on average, the probability of producing an economical grain yield was only 53.4% using this cultivar and the two sowing dates. This occurred primarily because most farmers in the study areas did not realize that they had been sowing maize during the high-risk window for extreme temperature (*T*max > 36 °C). The window was of importance particularly when it coincided with the

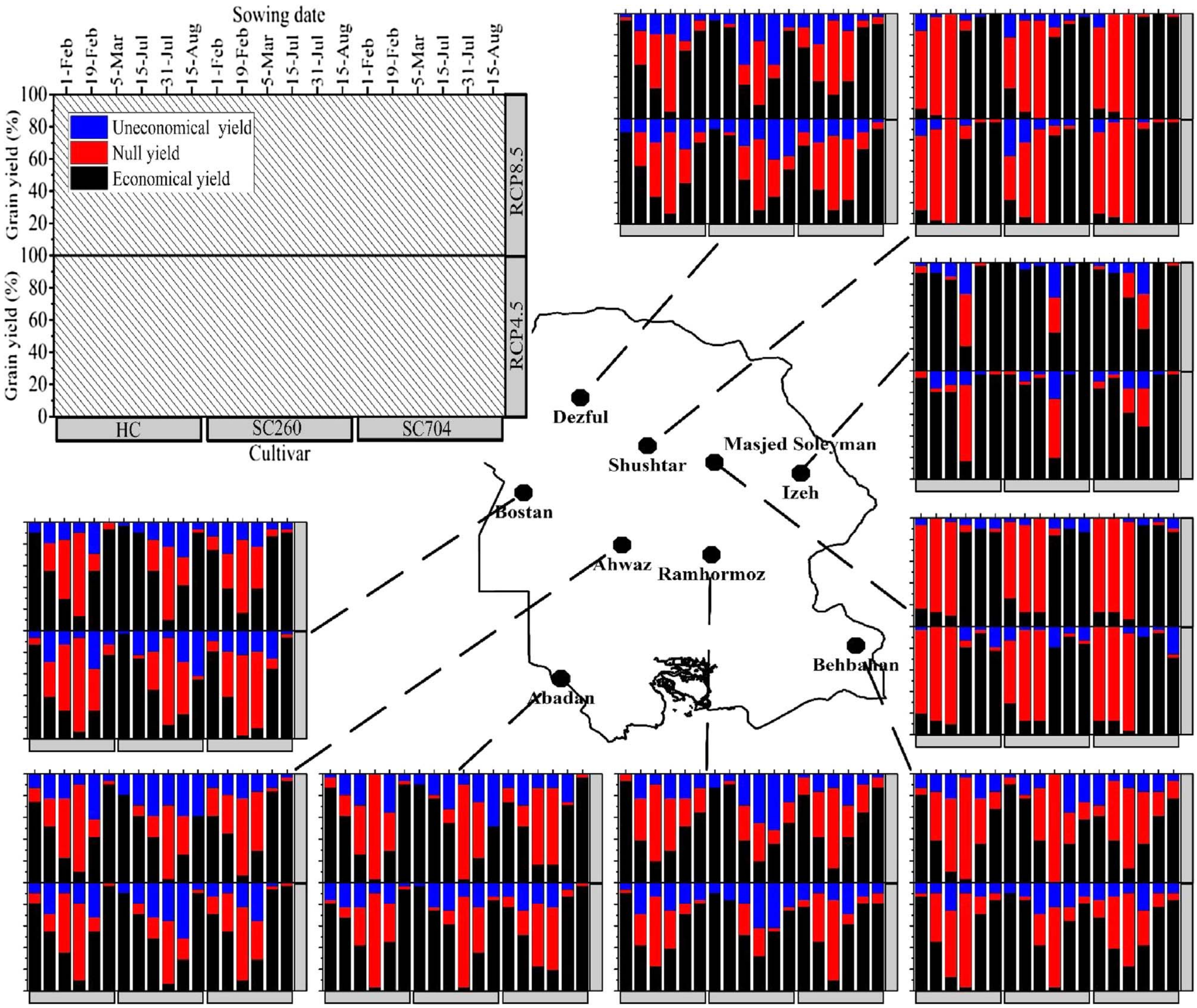

Fig. 6. Percentage of seasons with economical, uneconomical and null grain yields for sowing date × cultivar for both RCPs. Economical grain yield was ≥ 4.5 t ha^{-1} and uneconomical grain yield was < 4.5 t ha^{-1} (Agricultural Jihad Organization of Khuzestan province). Scales are given in this shaded box at the top-left of the figure.

flowering stage. Accordingly, choosing the wrong sowing date and the wrong cultivar decreased the economical grain yield and increased the uneconomical and null grain yields in some seasons at baseline.

The simulation results indicated that common winter sowing date × cultivar (19 February × SC704) resulted in 10 t ha^{-1} of economical grain yield while the common summer sowing date × cultivar (15 July × SC704) produced 8.6 t ha^{-1}. The simulated potential economical grain yield was much greater than these values (about 10.5 and 9.4 t ha^{-1} for the best sowing date × cultivar for winter and summer sowing dates), respectively. These 0.5 and 0.8 t ha^{-1} economical grain yield gaps (difference between potential yield at best sowing date × cultivar and yield obtained under common sowing date × cultivar) for the winter and summer sowing dates, respectively, was mainly caused by choosing wrong sowing date × cultivar under current conditions.

The area under maize cultivation in Khuzestan is 78,317 ha, making the average 0.65 t ha^{-1} yield gap equal to 1% of imports of maize by Iran (Anonymous, 2015). Anderson (2010) reviewed a range of environments (sites × seasons), cultivars, and levels of management (sowing times, fertilizer treatments, seed rates) in Western Australia to investigate the gap between actual and potential yield of rainfed wheat and concluded that the effect of environment accounted for about 80% of the variability in grain yield, while management and genotype accounted for about 6% and 3%, respectively. Kucharik (2008) investigated the relationship between maize grain yield and sowing dates from 1979 to 2005 in 12 central US states. In six of the 12 states, there was a significant relationship between sowing dates and yield. They found that management options have contributed to 19%–53% of the yield increases in Nebraska, South Dakota, Minnesota, Iowa, Wisconsin and Michigan and yield increases of 0.06–0.14 t ha^{-1} could be attributed to each additional day of earlier sowing. In another study Liu et al. (2013) showed that with the application of early planting dates and late-maturity cultivars, not only the negative effects of climate change eliminated, but also these two strategies improved grain yield due to an increase in the length of the maize growth season.

For winter sowing dates, SC260 did not perform well, but SC704 and HC were superior in the majority of locations. SC704 and HC performed similarly for early winter sowing dates. In late winter sowing dates, HC performed better than SC704 at all study locations except Bostan. For summer sowing dates, SC704 was the superior cultivar for the early date (except in Ahwaz); however, this cultivar lost its superiority when sowing was delayed until 15 August, in contrast to HC, in the majority of locations. Overall, late summer sowing dates with late-maturity cultivars performed best in terms of economical grain yield compared to early summer sowing dates and early-maturity cultivars.

Averaged across all locations and seasons, HC × 1 February and

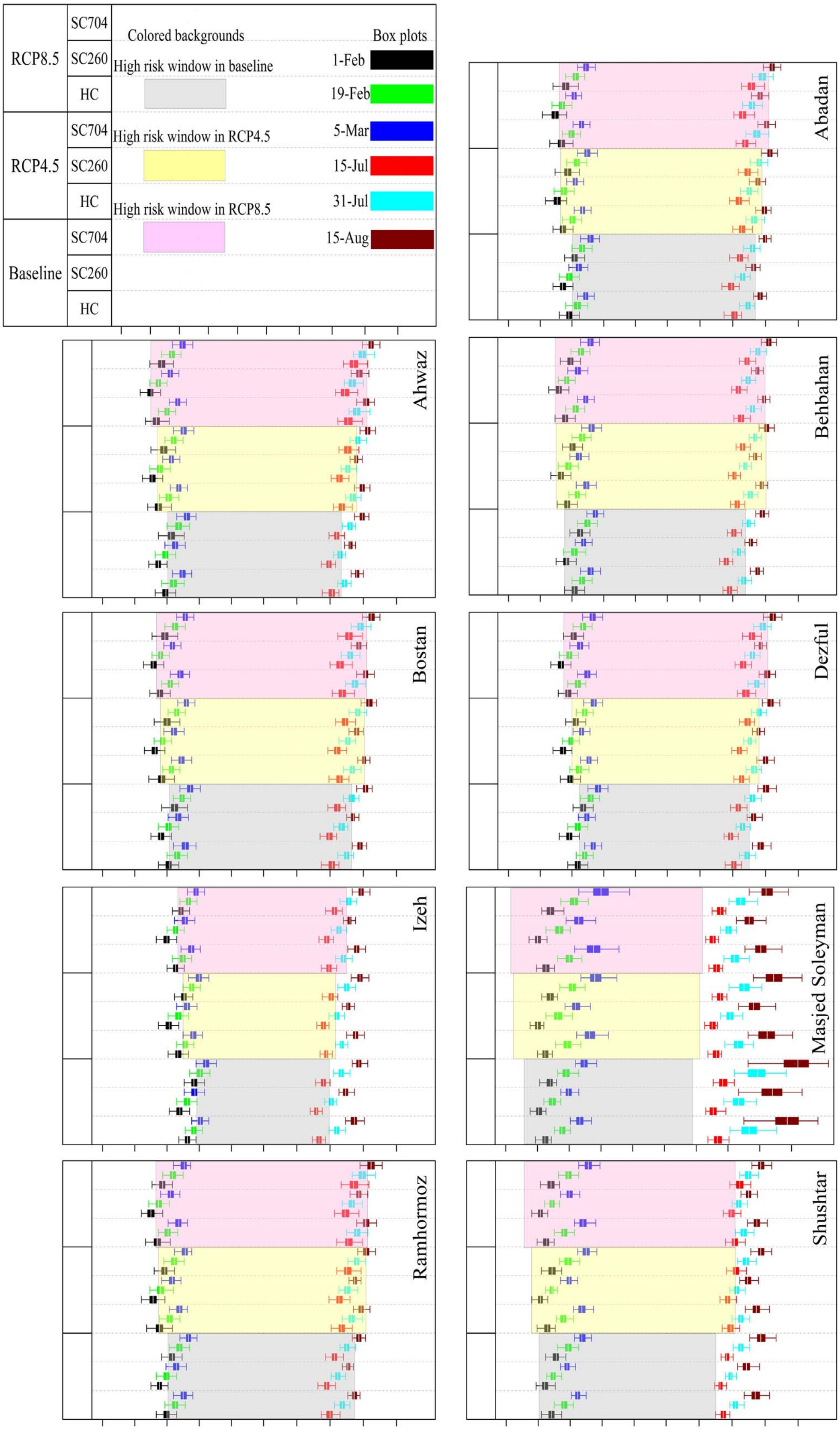

Fig. 7. High-risk windows for heat stress simulated by location, sowing date and cultivar at baseline and both RCP scenarios. The high-risk window was calculated as number of days with a maximum temperature of > 36 °C. The length of each box denotes variability in flowering time (DOY) across the 30-year simulation. HC was defined as the mid-maturity cultivar with characteristics between SC704 (late-maturity) and SC260 (early-maturity) and was obtained by modifying the genetic coefficients in APSIM. Scales are given in the bigger box at the top-left of the figure.

HC × 31 July were the most effective interactions for winter and summer seasons, respectively, with economical grain yields of 10.5 and 9.4 t ha^{-1} and a high probability of economical grain yield formation at 74.6% and 82.8%. Summer recorded a lower risk of producing both uneconomical and null grain yields (27.4%) compared to winter (38.5%) with average economical grain yields of 8.5 and 9 ha^{-1} for summer and winter, respectively. The reduction in overlap of the flowering stage with the extreme temperature window in summer

compared to winter decreased the risk of uneconomical and null grain yield formation. For example, average maximum temperature during the flowering stage in winter sowing dates (36.5 °C) was much higher than for the summer sowing dates (34.9 °C; data not shown).

Although summer showed a lower risk of uneconomical and null grain yields, it also recorded lower economic grain yield than winter. The reason for the higher economical grain yield in winter was optimal growing conditions. The cumulative global radiation and radiation absorbed by the canopy during the growing season in winter (3098 and 1585.2 MJ m^{-2}, respectively) was higher than for summer sowing dates (2636.9 and 1197.2 MJ m^{-2}, respectively; data not shown). The HC cultivar would be recommended to farmers at baseline because this cultivar showed a high grain yield and a lower probability of uneconomical and null grain yields formation, particularly for 31 July.

A similar study in southern Togo used DSSAT simulation to show that the optimum combination of cultivar × sowing date for maize were early sowing (12 April) with medium- or early-maturity cultivars because they produced higher yields and a lower risk of low yield (Bontkes and Wopereis, 2003). This study also indicated that sowing after the end of April slightly increased yields for the early-maturity cultivar as compared with the very early cultivar; however, the risk of a low yield was also higher.

The results of the current study revealed that for baseline conditions in Khuzestan province, selection of the best cultivar in combination with optimum sowing date is not as essential for farmers in heat stress-free regions such as Izeh because high economical grain yield was obtained 94.6% of the time (average yield of 10.5 t ha^{-1}). In warmer regions such as Shushtar and Masjed Soleyman, choosing the optimum cultivar × sowing date played a major role in increasing the number of years with economical grain yields and decreasing the number with uneconomical and null grain yields. For example, for the summer sowing dates, all cultivars were recommended for farmers in Shushtar, but for the winter sowing dates, none of the cultivars produced plausible economical grain yields.

The results of Kamara et al. (2009) are in line with the results obtained in the present study. They concluded extra-early maturing maize cultivars should be planted on the early sowing dates to decrease the risk of drought stress in the warmer conditions of the Sudan savanna (northeastern Nigeria). Their results also showed that a delay in sowing generally reduced dry matter production and grain yield.

4.3. The role of cultivar and sowing date in eliminating the negative impact of rising temperature on grain number and yield in future

Farmers in the study areas commonly cultivate SC704 on 19 February for winter sowing and on 15 July for summer sowing. If farmers continue with these management practices (management × genotype) under future climate change, they will significantly increase the risk of heat stress during flowering. Averaged across locations and RCPs, the probability of the number of seasons with null and uneconomical grain yields increased to 21% compared to baseline. Exposure of flowering time to the high risk window can reduce pollen viability and seed set (Hatfield and Prueger, 2015; Lobell et al., 2015) and will result in an increased number of uneconomical and null grain yields. This is demonstrated by the negative coefficients of regression for grain yield versus the number of flowering days at $T\max > 36$ °C in Fig. 8.

In the future, reducing the impact of heat stress on maize yield in the majority of regions could be done by adjusting the winter sowing time to ensure that the flowering stage occurs before May (except in Masjed Soleyman and Shushtar), before the maximum temperature has begun to rise dramatically. This type of adaption could be further improved by the use of early-maturity cultivars (SC260). By way of illustration, consider the SC704 × 19 February scenario as a common sowing date and cultivar in winter. Replacing only the early-maturity cultivar (SC260) with a late-maturity cultivar decreased the number of seasons with uneconomical and null grain yields 41.2% (average of RCPs and locations). Replacing only the early sowing date (1 February) with the late sowing date decreased the number of seasons with uneconomical and null grain yields 33.3%. Adjusting the early winter date (1 February) in combination with the early-maturity cultivar decreased the number of seasons with uneconomical and null grain yields 62.1%. In a similar study, Anderson et al. (2005) showed that under the climate change scenario in Western Australia, about 70% of the increase in wheat yield resulted from improved management practices such as adjustment of sowing date and chemical weed control and about 30% resulted from the use of appropriate cultivars.

For the summer sowing dates, the later sowing date (15 August) decreased the risk of heat stress during pre-flowering and flowering (81.5%) compared to the common summer sowing date (15 July). This increased economical grain yields and eliminated the number of seasons with uneconomical and null grain yields (9.9%). In early summer sowing, SC704, the late-flowering cultivar can flower after the high-risk window. This makes SC704 superior to HC in terms of flower formation outside the high-risk window. If moved to the late summer sowing date, HC could also flower after the high-risk window.

In addition to the decrease in the risk of null and uneconomical grain yields, the amount of economical grain yield is also important in the future. Under RCP4.5 and the early summer sowing dates, SC704 was superior for most study locations while under RCP8.5 and the early summer sowing dates, HC was superior in Bostan and Dezful and SC704 was in the other locations. In contrast, for the late summer sowing dates, both SC704 and HC showed similar good performance at all study locations. The reason for this is that the flowering stages always occurred after closure of the high-risk window at all locations.

For early winter sowing dates under both RCPs, SC704 and HC eliminated average yield loss at most locations. After a delay in sowing, only HC performed better than the other cultivars. Use of the early sowing dates and early-flowering cultivars (SC260) in winter decreased the length of flowering time exposed to the high-heat risk window. Although in winter SC260 on 1 February showed fewest null and uneconomical grain yields, this cultivar produced a lower economical grain yield than HC and SC704. Averaged for RCPs and location on 1 February, SC260, SC704 and HC produced 8, 10 and 10 t ha^{-1} of economical grain yield, respectively. Although SC704 and HC had the same economical grain yield (10 t ha^{-1}), HC produced fewer null and uneconomical grain yields (29.2%) compared to SC704 (39.4%). The coincidence of the flowering period with the high-risk window decreased the grain yield mainly due to the decline in grain number (Dupuis and Dumas, 1990; Herrero and Johnson, 1980).

Moradi et al. (2013) investigated irrigation water and sowing dates as adaptation strategies to reduce the impact of climate change on maize production in Khorasan-e Razavi province in northeastern Iran. They found that the early sowing date (1 May) increased yield compared to the other sowing dates by allowing better adaption to high temperatures. Deryng et al. (2011) in their simulation study, reported that changing the sowing date and cultivar could mitigate the negative impact of climate change on world food production. This would avert the predicted global yield loss of 18% for maize, 12% for spring wheat, and 7% for soybeans.

The summer sowing dates generally exhibited lower risk of uneconomical and null grain yields compared to winter sowing dates. When summer and winter sowing dates were compared, the number of seasons with both uneconomical and null grain yields was much higher for winter sowing dates (50.4%) than summer sowing dates (37.8%) in 2050. When both future scenarios were averaged, winter sowing dates performed better (8.5 t ha^{-1}) than summer sowing dates (7.8 t ha^{-1}) in terms of economical grain yield. This reason is mainly due to better environmental conditions over the growing season in winter. For example, cumulative global radiation and its absorption by the canopy during the growing season for winter sowing dates (3003.8 and 1583.6 MJ m^{-2}, respectively) was much higher than for the summer

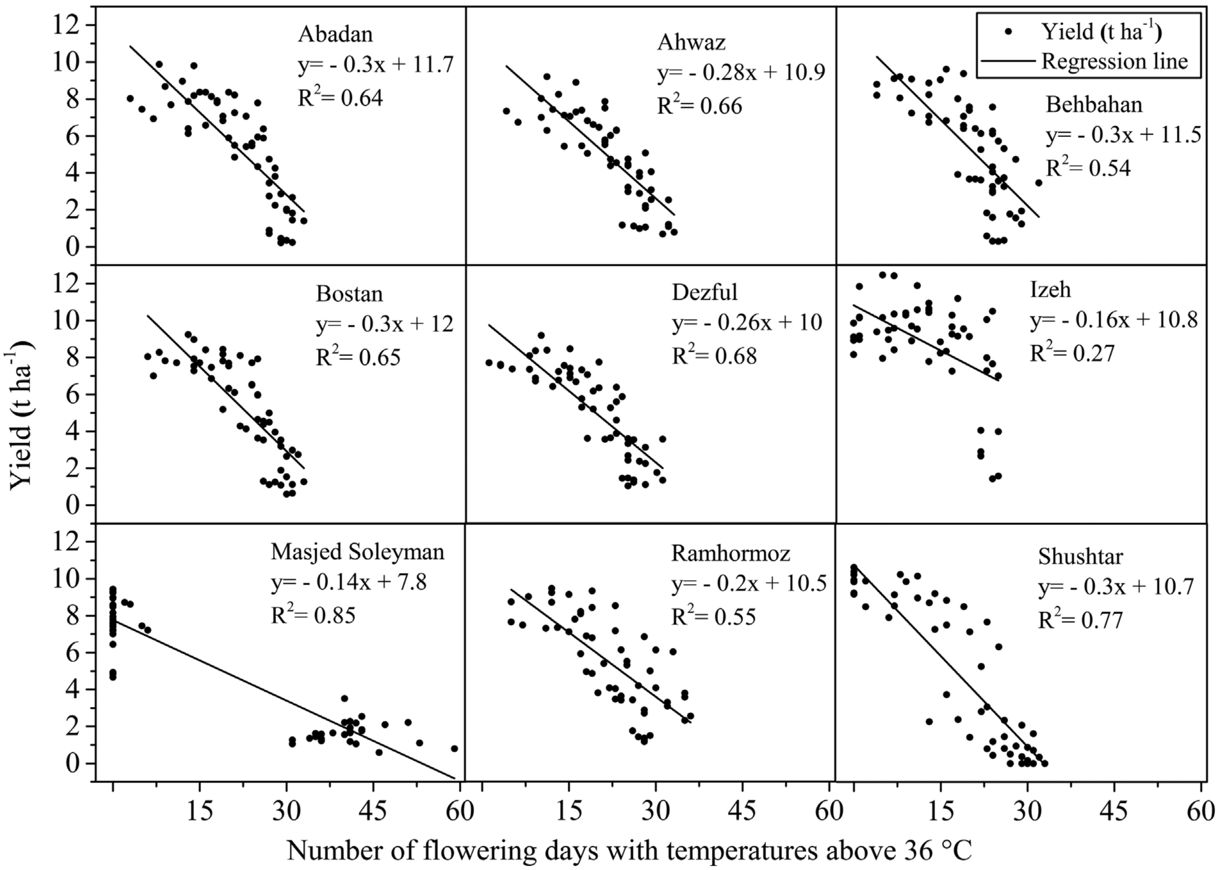

Fig. 8. Regression analysis of grain yield and number of flowering days at temperatures of > 36 °C at different locations.

sowing date (2590.5 and 1097.1 MJ m^{-2}, respectively; data not shown). During years with economical grain yield formation, the mean temperature over the growing season was only slightly higher for summer sowing dates (27 °C) compared to winter sowing dates (26.7 °C; data not shown).

Overall, the lowest uneconomical and null grain yields (9.9%) were recorded for late-maturity cultivar × late sowing date in summer. This interaction decreased exposure to high-risk windows. The average maximum temperature during flowering for this interaction (32.6 °C) was less than the maximum critical temperature for flowering (Tmax > 36 °C) as compared to the other interactions. Despite the decreased risk of uneconomical and null grain yields for summer sowing dates, farmers must accept a decrease in economical grain yield (8%). On the contrary, for the winter sowing dates, farmers must accept increased risk of heat stress despite the higher economical grain yield. The recommended combination for winter was HC × 1 February and for summer was SC704 × 15 August in 2050 in terms of decreasing the risk of uneconomical and null grain yields and increasing economical grain yield.

4.4. Breeding strategies to cope with risk of extreme temperatures

The expansion of the high-risk window in the future scenarios for Khuzestan caused the flowering stage fall within the longer extreme temperature windows. The coincidence of the flowering stage with the high-risk window was strongly dependent upon location, cultivar and sowing date. In the future, early-maturity cultivars (SC260) at early sowing dates (1 February) experienced less time in the high-risk window during flowering stage for all winter sowing seasons for both scenarios and throughout all locations except Masjed Soleyman and Shushtar. For example, the common sowing date (19 February) and cultivar (SC704) in Izeh for a flowering period from 18 May to 22 May (5 days) fully exposed the flowering stage to the high-risk window under RCP8.5 (10 May–12 October; 156 days). Shifting to the earlier date (1 February) in combination with the early-maturity cultivar (SC260) allowed the flowering stage (27 April–2 May) to occur outside the high-risk window. As another example, the flowering stage of the 19 February × SC704 combination in Dezful (10 May–14 May; 5 days) fully coincided with the high-risk window under RCP4.5 (30 April–21 October; 174 days). Changing the combination to 1 February × SC260 allowed the flowering stage (19 April–22 April; 4 days) to occur outside the high-risk window.

After assessing the dates of the high risk windows, for which there is the highest incidence of uneconomical and null grain yields, and the decrease in economical grain yields under climate change conditions, two maturity cultivars were recommended for hot areas such as Khuzestan province. For winter cultivation of maize, the early-flowering HC cultivar with a high post-flowering period can reduce production risk and increase grain yield. The hypothetical cultivar in this study recorded higher economical grain yield under winter cultivation than the other cultivars in most locations

The higher grain yield could be attributed to the genetic coefficients of the HC cultivar. The HC has a thermal time accumulation from seedling emergence to the end of juvenile phase of 250 °C d and from the end of the juvenile phase to floral initiation of 0 °C d. These are lower than for SC704 (270 and 30 °C d, respectively) and allow flowering earlier in comparison with SC704 to avoid exposure of the flowers to the high-risk window. Early-maturity cultivars require less corn heat units to reach flowering and late-maturity cultivars have extended vegetative periods Kamara et al. (2009). Note that, although the HC cultivar sets flower later than the SC260, it recorded a higher economical grain yield that can be attributed to the longer post flowering period (thermal time accumulation from flowering to maturity of 1000 °C d) than SC260 (thermal time accumulation from flowering to

maturity of 780 °C d).

Genetic improvement mostly accounted for the significant yield increases and heat stress tolerance in recent decades. A survey on breeding for heat tolerance in potatoes showed genetic gain after recurrent selection for heat tolerance which resulted in a strong increase in yield of 37.8% (Benites and Pinto, 2011). Edmeades (2013) stated that genetic improvement for heat-drought tolerance in maize created improvements of 20%–25% in the yield gap between drought-affected and optimal situations. Conventional selection by CIMMYT for drought tolerance focused on yield and associated secondary traits and resulted in gains of about 100 kg ha^{-1} yr^{-1} in tropical maize populations. Selection by the private sector of temperate germplasm, through multi-location trials for common yield has shown gains during drought of about 65 kg ha^{-1} yr^{-1}.

The current study did not examine tolerance as a resistance strategy (Chaves et al., 2003) but focused on escape strategies. The coincidence of a sensitive stage like flowering with heat stress decreases the yield for both sensitive and tolerant cultivars (Lobell et al., 2015). In such situations, an escape strategy could avert the flowering of both cultivars from occurring during a high-risk window. Breeding strategies for winter maize cultivation in hot areas such as Khuzestan province should focus on genetic coefficients similar to that of the HC cultivar with shorter pre-flowering and longer post flowering periods.

For the summer sowing dates, the late-flowering cultivar (SC704) experiences the flowering stage well outside the high-temperature risk window, which decreases the risk of heat stress and increased economical grain yield. The SC704 has a thermal time accumulation from seedling emergence to the end of juvenile phase of 270 °C d and a thermal time accumulation from end of juvenile to floral initiation of 30 °C d. This is an advantage over other cultivars because it allows flowering to occur outside the high risk window and the high-risk window occurs from late April to late October in all future scenarios. For the summer sowing dates, the high value for thermal time accumulation from seedling emergence to the end of juvenile phase delayed flowering until after October. In addition, SC704, with its longer growth period and higher number of grains per head produces a higher grain yield.

Scientific reports also verified that cultivars with longer growth periods (Liu et al., 2013; Sharma et al., 2008; Zhang et al., 2006, 2012) and a higher number of grains per head produce higher yields. For summer cultivation in hot areas, breeding recommendations should be for late-flowering cultivars like SC704 with long pre-flowering period (high values for thermal time accumulation from seedling emergence to the end of juvenile phase and thermal time accumulation from end of juvenile to floral initiation), long reproductive growth period (high values for thermal time accumulation from flowering to maturity) and a high number of grains per head.

5. Conclusion

The results of model evaluation indicated that the APSIM-maize model could be successfully applied to simulate maize grain and biomass yields under hot climatic conditions. The results also revealed that the common sowing dates (19 February and 15 July for winter and summer sowing dates, respectively) and the cultivar (SC704) currently used by most farmers in the study locations are not optimal at baseline. Most farmers have not realized that they sow maize during a high-risk window for extreme temperatures (Tmax > 36 °C) in some seasons. The high-risk window in the future will lengthen. If farmers do not apply adaptive options for their regions (most promising sowing date × cultivar), the probability of economical grain yield will be less than 50% for an average economical grain yield of 8.9 t ha^{-1}.

Adapting maize cropping systems under hot conditions through management practices (sowing dates) and breeding strategies (improving suitable cultivars) will result in an economical grain yield advantage of 0.6–1.1 t ha^{-1}, depending on the location. In addition to increased grain yield, the probability of occurrence of the economical grain yield will be increased to 80.5% by 2050. The current findings support the hypothesis that climate change by the middle of the 21st century will not be beneficial for maize agroecosystems in hot areas like Khuzestan province unless the best sowing date × cultivar is applied for both winter and summer sowing dates.

Acknowledgments

The authors are grateful to Prof. Graeme L. Hammer from the University of Queensland, Australia for providing valuable comments and his advices on methodology. We also thank from Dr. Eskandar Zand from the Iranian Research Institute of Plant Protection for providing data for model evaluation.

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